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Field study on concrete footpath with recycled plastic and crushed glass as filler materials

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HIGHLIGHTS

- 10% recycled plastics & 10% crushed glass as coarse aggregate replacement in concrete.
- Unconfined compressive strength, indirect tensile strength and capillary water uptake.
- Utilizing recycled plastic and crushed glass in concrete footpath was satisfactory.
- Schmidt hammer test results satisfied the strength requirement for concrete footpaths.

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ABSTRACT

Generation of plastics and glass wastes is rapidly increasing world-wide due to the heavy consumerism culture of modern societies. The disposal of single-use packaging products imposes a substantial toll on the environment. A large fraction of this waste ends up in landfills causing pollution in both marine and land environment. Sustainable applications of utilizing such waste material which can reduce the landfill requirement for the glass and plastic wastes acquires global attention. In this study, recycled plastic waste (RPW) and recycled crushed glass (RCG) were mixed in concrete and a field trial was conducted for concrete footpaths in the state of Victoria in Australia. Samples of the concrete mix were collected and the mechanical properties such as unconfined compressive strength, indirect tensile strength and capillary water uptake was tested in laboratory. Non-destructive field test using the Schmidt hammer was carried out to evaluate the compressive strength of various points located on the footpath and the results were compared with the standard set by local authorities. Result of this field study indicated that the concrete design mix containing 10% RPW and 10% RCG (volume percentage) meets the local council standard used in concrete footpath construction.

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1. Introduction

The negative environmental impact of plastic waste has increasingly drawn the global attention. Plastic waste significantly burden both land and marine environments, including water pollution and soil contamination, threatening the wildlife survival inland and in the oceans [1–3]. Global production of plastic, including products and packaging, has increased sharply from 1.7 million tonnes per year in 1954 to 348 million tonnes per year in 2017 [4]. According to Sustainability Victoria [5] of Australia, the quantity of plastic waste generated in 2016–17 was approximately 553,000 tonnes, of which only 24% was recovered. Although the recovery ratio in 2016–17 was increased by 10% compared with a decade earlier, about 422,000-tonne plastic waste was still directly landfilled [5]. Plastic waste has the lowest recovery rate (24%) compared with other types of wastes, such as metals (96%), construction & demolition (81%), paper/cardboard (75%) and glass (62%). In contrast, the recycling performance of glass waste was much better compared with plastic waste. During the same period (2016–17), 137,318-tonne glass waste was recovered, and the amount of landfilled glass waste was 82,202 tonne [5]. More than 60% of glass waste generated in Victoria was recovered in 2016–17. It was worth noting that in 2016–17, the recovery ratio of glass waste also had lowered compared with 10 years ago. All these data indicated that it is rather urgent to find alternative recovery routes for the plastic and glass wastes.

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Singh et al. [6] reviewed the feasibility of using plastic waste in various fields such as primary recycling of uncontaminated plastics back into plastics injection moulding and secondary recycling for contaminated plastics that is recycled as different products. Plastic waste can be reused as both filler and binder materials. For example, polyethylene terephthalate (PET) fibres with high tensile strength was found to benefit both the compressive and tensile strength of high water/cement ratio concretes [6], and plastic waste formed in fibre strand with low tensile strength improved the mechanical properties of concrete with low water/cement ratios [7–9]. In addition, the wood plastic composite was also good practice of utilising plastic waste as binder materials [10,11]. Fraternali et al. [8] studied the behaviour of high-performance cement-based mortar and recycled polyethylene terephthalate strips with different lengths (11.3 mm–35 mm). They reported that recycled polyethylene terephthalate strips decreased the first-crack strength of the cement-lime mortar while the 35 mm strips featured the best reinforcement performance in both first-crack strength and post crack response among other tested strips. Saikia and De Brito [12] used various types and shapes of plastic as aggregate in concrete and they found that the workability and strength properties of concrete depend on the size and shape of plastic aggregates. The incorporation of plastic aggregates lowered the strength properties of concrete and mortar due to the low binding strength between plastic flakes and cement.

The recovery of glass waste has also been researched extensively. The main application of glass waste was for construction materials, such as concrete [13], asphalt [14] and bricks [15]. Due to the characteristic of low water absorption of glass particles, construction materials utilising glass waste showed a relatively low water absorption ratio compared with ordinary materials [16]. However, the smooth particle surface and harmful alkali-silica reaction caused detrimental effects on concrete properties when glass waste was used as aggregates [17,18]. It was found that the particle size of glass waste significantly influenced the properties of concrete [19]. Properties of concrete with fine aggregates partially replaced by glass waste was studied by Ismail and Al-Hashmi [16] and they concluded that 20% waste glass blend increased the flexural strength and compressive strength properties by 11% and 4% compared with control blend respectively. Lam et al. [20] stated that 50% recycled glass and 50% recycled fine aggregates (<5 mm) blended with 10% pulverised fuel ash admixture were used to manufacture quality pavement blocks. They recorded the bricks UCS value of 70 MPa and tensile splitting strength of 4 MPa after cured for 28 days. Ling et al. [21] reported that flexural and compressive strength of the concrete decreased with the increased in glass content and the flexural strength was found to be about one-sixth of the compressive strength of a cement mortar blend with 100% recycled glass replacing the fine aggregates.

Despite a wide range of studies have been conducted in utilizing plastic and glass wastes, most of them were laboratory-based [6–9,16–18]. This research presents the characteristics and performance of a concrete footpath constructed in Victoria, Australia, utilising plastic and glass wastes as aggregates. The field trial demonstrated the viability of using plastic and glass aggregates in concrete footpath construction in comparison to the conventional footpath. The optimal composition of plastic and glass waste obtained in the previous project [22] was selected. In this field trial, plastic and glass wastes, played the role as filler materials in concrete footpaths, substituting the raw materials such as aggregates, sands and other base materials. Replacing these raw materials with recycled plastics and glass wastes reduced the use of virgin materials as well as lower carbon emissions. On the other hand, hardened concrete footpaths immobilised plastic and glass wastes, diverting a significant quantity of waste materials from being stockpiled in landfills. This action decreased their adverse impacts on the environment.

2. Field trial methodology

2.1. Site description

The concrete footpath was constructed at Geddes Crescent Park in Hoppers Crossing, Victoria (see Fig. 1). The total length of the concrete footpath was approximately 339 m with the width of 1.5 ± 0.05 m and depth of 100 ± 5 mm. A local construction company was contracted to carry out the construction project and provided a total volume of 50 m^3 of concrete mix. Section A of the concrete footpath as shown in Fig. 1 was constructed with M40 concrete only and considered as the control section of this field study, while Section B and C were constructed with the concrete mix which contains recycled plastics and crushed glass materials.

2.2. Materials

The concrete mix used in this research included General Purpose (GP) cement, gravel (20 mm minus), sand, recycled plastic waste (RPW) and recycled crushed glass (RCG). The GP cement, gravel and sand were commercially obtained and these products were used in conventional concrete mix too. The RPW and RCG were supplied by a local recycling company. The chemical compositions of RCG and GP cement is shown in Table 1. Since the RPW and RCG were derived from kerb-side wastes by pulverisation, the particles are in fragments as shown in Fig. 2. The particle sizes of RPW and RCG were less than 5 mm and 3–8 mm, respectively. The design mix of the concrete footpath was 10% RPW and 10% RCG (based on volume percent of the sample mix) of a grade M40 concrete. Fig. 3 shows the construction process of the footpath at Geddes Crescent Park. Fig. 3(a) is a photo image of the foundation formwork before the concrete pouring. Fig. 3(b) a photo image showing the pouring of the concrete footpath and Fig. 3(c) a photo image of the concrete footpath after 28 days of construction.

2.3. Methods

A typical M40 mix design concrete (targeting 28 days strength value of 40 MPa) commonly used by Victorian local council was adopted and modified for partial plastics and glass replacement. The mix design for the concrete incorporating 10% RPW + 10% RCG is presented in Table 2. This particular mix design was selected based on our earlier work [22] which maximise the use of recycled plastics and glass fines wastes in concrete as filler materials. The equivalent weight percentages of RPW and RCG in the mix design is presented in Table 2. Cylindrical concrete samples with a diameter of 100 ± 1 mm and height of 200 ± 2 mm were prepared according to the ASTM C31[23] during the construction of the footpath for laboratory strength evaluation tests. Concrete samples were cured by submerging in water as detailed in ASTM C31 and the samples were later tested for its mechanical properties.

Unconfined Compressive Strength (UCS) test was conducted using ASTM C39 [24] for 3 days, 7 days, 14 days and 28 days cured samples. The top and bottom surfaces of each sample were polished after curing to obtain a smooth flat surface before UCS test. Three samples of the same dimensions were used in UCS tests and the average value was reported. A loading rate of 0.33 MPa/s was applied on the samples and the maximum stress value of a sample was recorded before failure.

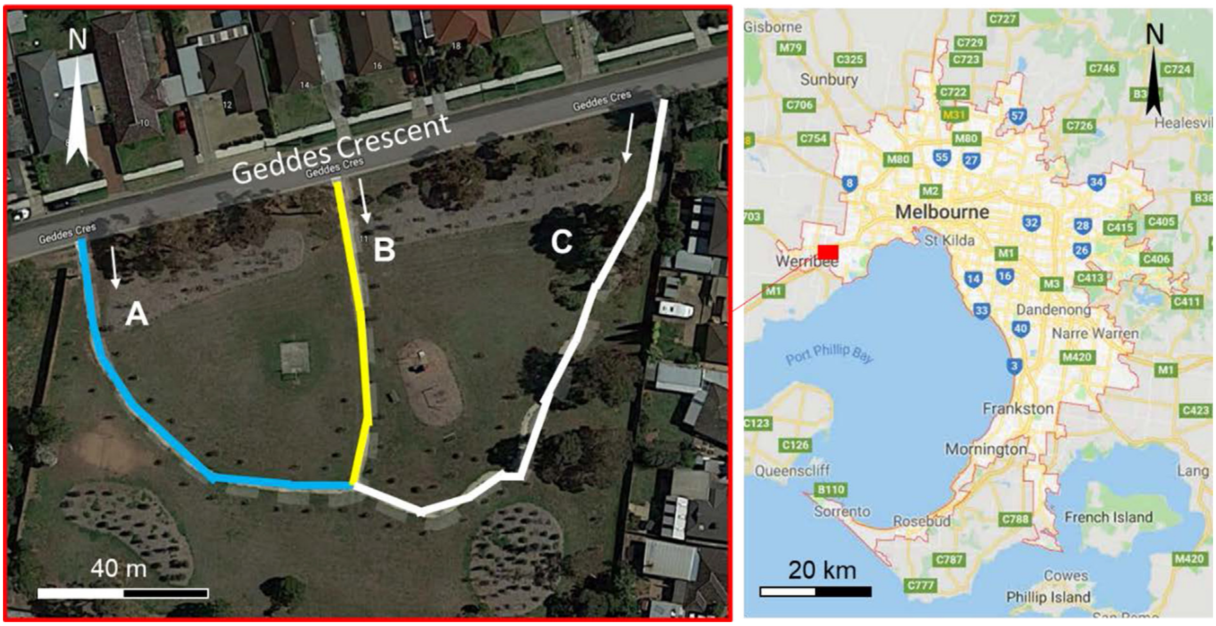


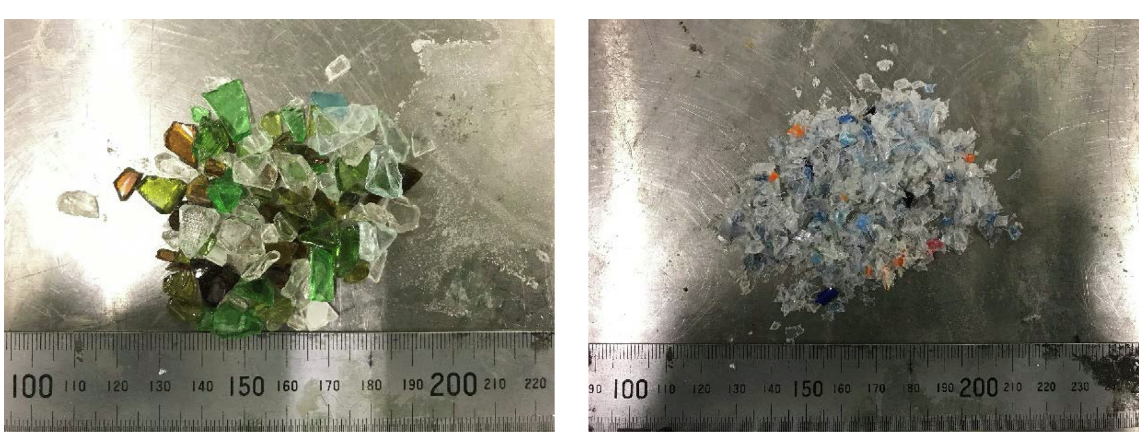
Fig. 1. Site location of the field-trial concrete footpath [28].

Table 1
Chemical compositions of RCG and GP cement.

Oxides	Weight (%)	
	RCG	GP cement
Na_2O	12.60	0.3
MgO	3.68	1.1
Al_2O_3	1.03	4.5
SiO_2	69.10	20.2
P_2O_5	0.07	–
SO_3	0.21	2.7
K_2O	0.28	0.3
CaO	9.17	63.0
TiO_2	0.06	–
MnO	0.01	–
Fe_2O_3	0.47	4.5
LOI	3.24	3.4
Norm. Factor	1.03	1.03

The Silver Schmidt hammer test is a reliable non-destructive test which is often used to evaluate the surface hardness of materials in both field and laboratory. Silver Schmidt hammer testing measures the "Q-value" of an impact location and converts the value into an estimated compressive strength value based on an empirically derived function. Empirical equations developed by previous studies [25,26] reported that Schmidt hardness rebound values showed a reliable relationship with UCS of hard materials such as rock and concrete. For the purpose of this fieldwork, the European reference curve function and a carbonation factor of 1.0 was adopted as recommended by the Silver Schmidt Hammer operation manual for testing 28-days-cured concrete.

In-direct Tensile (IDT) tests were carried out in accordance with ASTM C496 / C496M-17 [27] for the samples prepared at site in accordance with ASTM C31 [23]. The IDT tests were carried out for the 3 days, 7 days, 14 days and 28 days cured cylindrical concrete samples having a diameter of 100 ± 1 mm and height of 200 ± 2 mm. A vertical compressive load was applied diametrically across the circular cross-section of the samples at a constant tensile stress rate having a range of 0.7–1.4 MPa/min until the sample reached to its failure point. Maximum stress during the failure was recorded for all three cylindrical samples and the average value was calculated.



A) Recycled crushed glass B) Recycled plastic waste

Fig. 2. Photograph images showing A) RCG and B) RPW.

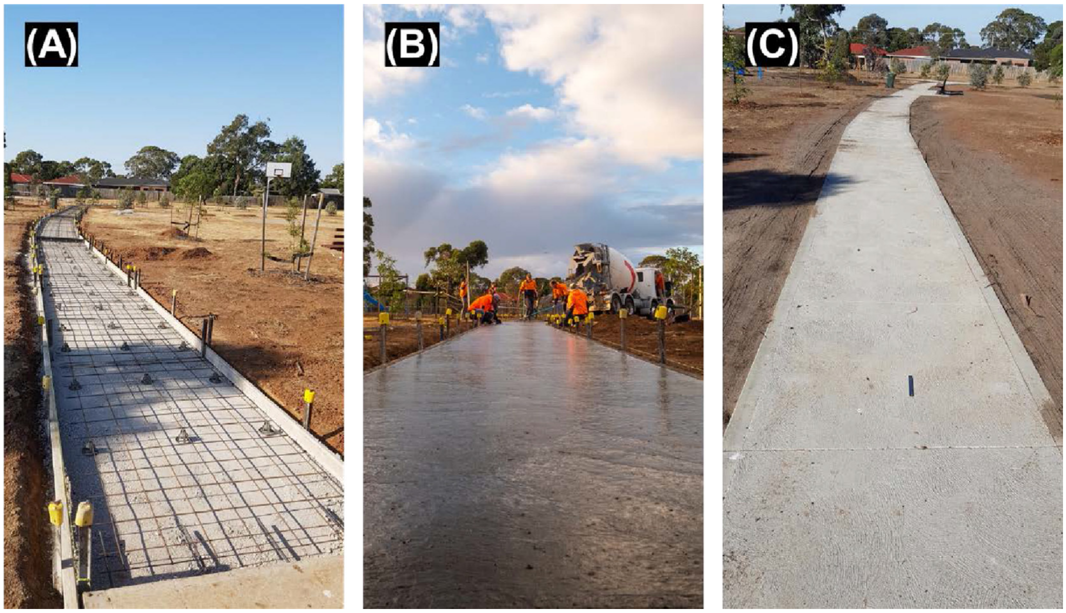


Fig. 3. Construction process of the field-trial concrete footpath: A) Before pouring concrete, B) Concrete pouring, and C) 28 days after concrete pouring.

Table 2
Typical ingredients of M40 concrete with 10% RPW + 10%RCG mix design for 1 m^3.

Material	Amount
Water (kg)	158
Cement (kg)	400
Fine aggregates (kg)	558
Coarse gravel aggregates (kg)	1172
RPW aggregates (kg)	52.2
RCG aggregates (kg)	110.6
Water : Cement ratio	0.4
Admixture (kg)	2.8
Total (Tonne)	2.22

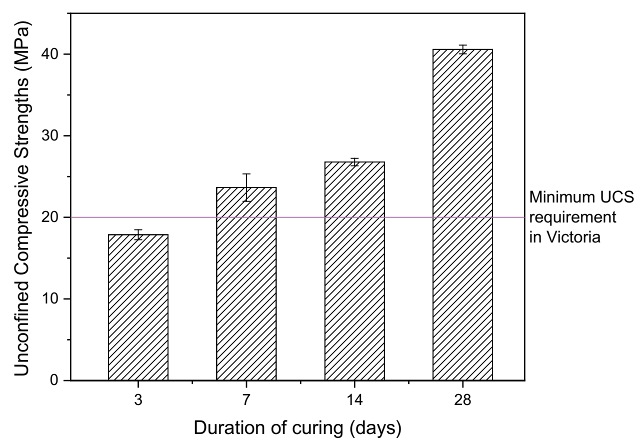


Fig. 4. Development of the UCS values of the concrete sample.

The water absorption of the samples by capillary uptake properties with time was evaluated for the cubic concrete samples having dimensions of 50 mm × 50 mm × 50 mm. Samples were prepared at site using steel moulds and care was taken to exclude coarse aggregates (17 mm plus). Samples were submerged in water for 28 days before the test. Test samples were were dried in an oven at 104 °C for 24 h before testing. Water absorption tests were carried out in accordance with ASTM C1403-15 [28].

3. Results

3.1. UCS test

The average UCS of the samples tested along with its curing days is presented in Fig. 4. The average UCS values were calculated from three cylindrical concrete samples and the standard deviation of the samples is also presented in Fig. 4.

3.2. Schmidt hammer test

The Silver Schmidt hammer test was adopted as a non-destructive test to evaluate the surface hardness of each footpath sections and the results was used to validate the laboratory UCS test results for the samples of the same design mix concrete. The test was conducted 28 days after the concrete footpath was constructed. The surface of the concrete was slightly polished to make the surface smooth for the Schmidt hammer test. Test locations were positioned on the concrete footpath at approximately 2.0 m intervals across all footpath alignments within the reserve. At each test chainage (denoted as CH), 3 tests were conducted separately on the left (LHS), centre (MID), and right (RHS) side of the footpath at approximately 0.5 m spacing. Ten impact readings were taken at a single point and the average value was calculated for each point along the footpath sections. All measurements taken indicated standard deviations of ≤ 5.0 Q-value as recorded by the Schmidt hammer. The UCS values of the concrete footpath at the MID, LHS and RHS of section A, B and C (see Fig. 1) are presented in Fig. 5(a), (b) and (c) respectively. The summary of the average 28-days UCS values of the footpath sections tested by Schmidt hammer is presented in Table 3.

3.3. IDT test

A typical cross-section of cylindrical sample after IDT test is shown in Fig. 6 and the average IDT values of the tested samples is shown in Fig. 7. As shown in Fig. 6, the tested concrete footpath is a mix of 10% RPW and 10% RCG and coloured fragments of RPW

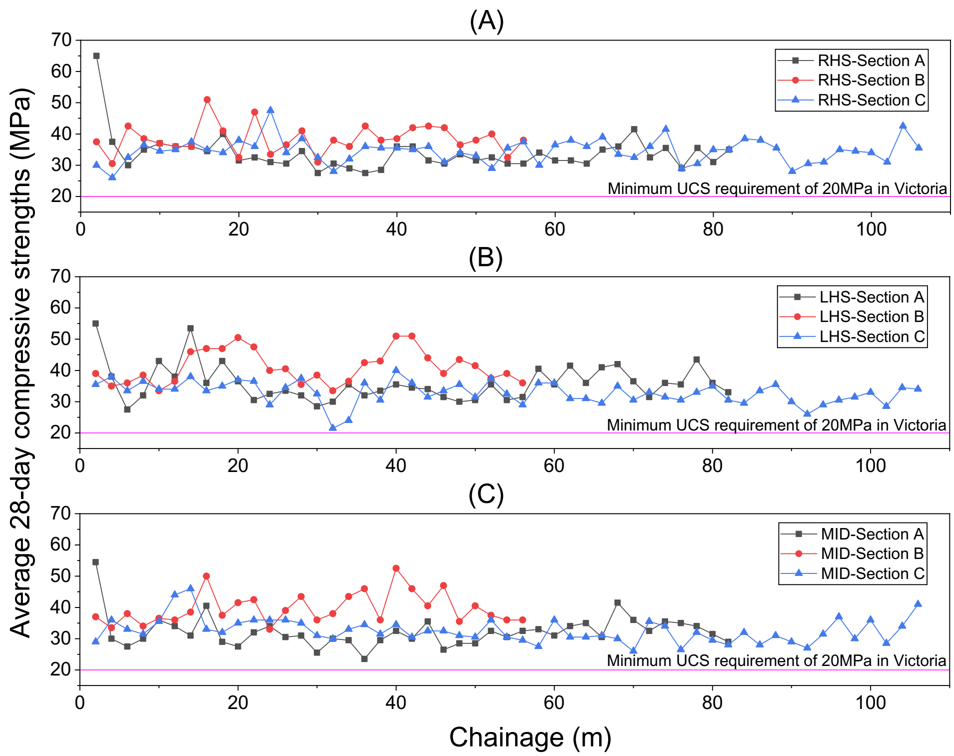


Fig. 5. Schmidt hammer compressive values along the footpath sections: A) Right-hand side, B) Left-hand side, and C) Middle.

Table 3
Summary of the average Schmidt hammer test UCS values of the footpath sections.

Section	Section A	Section B	Section C
Average UCS-MID (MPa)	32.22	39.70	32.59
Average UCS-LHS (MPa)	35.91	41.04	32.87
Average UCS-RHS (MPa)	33.78	38.43	34.57

Fig. 6. A Typical cross-section of a M40 Concrete + 10% RPW + 10% RCG cylindrical sample after IDT test.

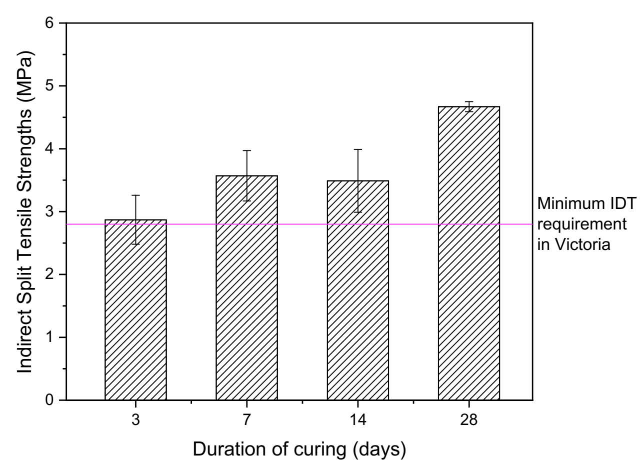


Fig. 7. Development of the IDT values of the concrete sample.

and RCG particles are visible at random spaces on the internal surface of the rectangular cross-section of the split sample.

3.4. Water absorption test

Fig. 8 shows the water absorption results of 28-days for samples with and without 10% RCG and 10% RPW. Fig. 9(a) is a photo image of a thin section cut from the water absorption cube sample showing evidence of the argument that the concentration of RPW volume is rather high at the top layer of the sample. Fig. 9(b) is an optical micrograph of the thin section of the water absorption sample showing the presence of voids between RPW and concrete on the surface.

4. Analysis and discussion

4.1. UCS test

According to the Fig. 4, significant increase of the UCS values can be observed in the tested samples along with the curing time. The minimum UCS requirement of 20 MPa for the concrete used in footpaths in the state of Victoria [22] has been exceeded by the tested 10% RPW + 10% RCG concrete mix in between the day 3 and day 7. Furthermore, the strength requirement for the concrete used in footpaths set by different city councils such as Casey [29], Monash [30] and Wyndham [31] is reported as 25 MPa. However,

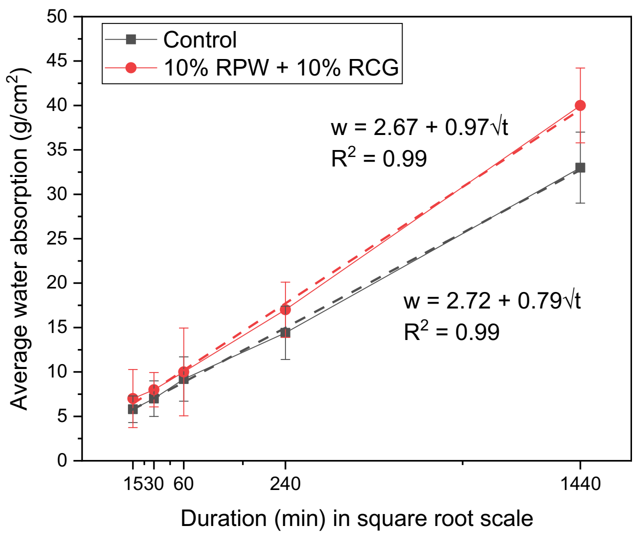


Fig. 8. Water absorption results of the field trial samples.

the average UCS values of the tested samples exceeded the 40 MPa compressive strength of 28 days.

4.2. Schmidt hammer test

According to Fig. 5, all sections showed a UCS value well above the minimum UCS requirement for the concrete footpath that is 20 MPa. A recent study by Bostanci [32] using recycled glass (5.6 mm minus) as a 20% mass replacement of sand in concrete reported 40 MPa for the average 28-days UCS and 28 MPa for the average 28-days by Schmidt hammer test. The UCS and Schmidt hammer test values in this study is in close agreement with Bostanci [32]. Soft spots within the control section (Section A) were identified at CH.6, CH.20, CH.30, CH.36, and CH.46 to CH.50, which comprises 25.9% of the Schmidt hammer test readings on the section with a minimum recorded 28-days concrete strength of 23.5 MPa. No soft spots were identified within Section B comprising the sustainable concrete trail mix. Throughout all of Section B, all test locations showed a minimum 28-days concrete strength of $\geq$30 MPa. Soft spots within the Section C were identified at CH.4, CH.32, CH.34, CH.58, CH.70, CH.76, and CH.92, which comprises 13.2% of the SSH test readings on the section with a minimum recorded 28-days concrete strength of 21.5 MPa.

According to Table 3, the average 28-days Schmidt hammer test UCS values of section A, B and C of the footpath were within 32–41 MPa range and section B showed a higher average 28-days UCS values when compared with Section A and C. However, in MID and LHS average UCS values of Section A and C showed a minor difference when compared with the Section B value. However, a similar study by Topçu and Canbaz [33] which contained 20% of recycled waste glass in concrete reported 33 MPa value for the 28-days UCS by Schmidt hammer test and that value was similar to Schmidt hammer test UCS values evaluated in this study.

4.3. IDT test

According to the Fig. 7, there is a gradual increase of the IDT values of the 10% RPW and 10% RCG concrete samples with days of curing. However, the 14-days average IDT values of the tested sample showed a slight decrease. The cylindrical concrete samples were made at the site and the concrete mix used was randomly sourced from different cement trucks. Even though the concrete was well mixed with 10% RPW and 10% RCG, the distribution of the RPW and RCG amounts would be randomised because each batch of concrete mix was approximately 5 m^3 per truck. The slightly decreased IDT value of the 14-days cured sample could be due to having comparatively high amount of RPW and RCG particles at the split surface. Nevertheless, all the tested samples exceed the average splitting tensile stress value of 2.8 MPa set by ASTM C496/496 M−17 [27] for the cylindrical concrete sample. Closely related IDT test results were reported by Huang et al. [34] for the concrete samples containing recycled asphalt pavement as partial replacement of coarse and fine aggregates. Moreover, a similar study by Topçu and Canbaz [33] reported that IDT values for the concrete samples containing waste glass percentages from 0% to 60% were within the range of 1.63–2.53 MPa and the decreased in IDT values was reported as 37%. In addition, Park et al. [35] reported a decreased of 5% of IDT value for the concrete containing 30% addition of waste glass.

Both RPW and RCG used in this footpath research had smooth surfaces when compared with the rest of the aggregates used in the concrete blend. As shown in previous studies [12,33,35], incorporation of plastic and glass aggregates lowered the UCS values, IDT values and tensile strength of the control blends due to the low binding strength between RPW/RCG flakes and cement. It should be noted that the objective of this study is mixing RCG

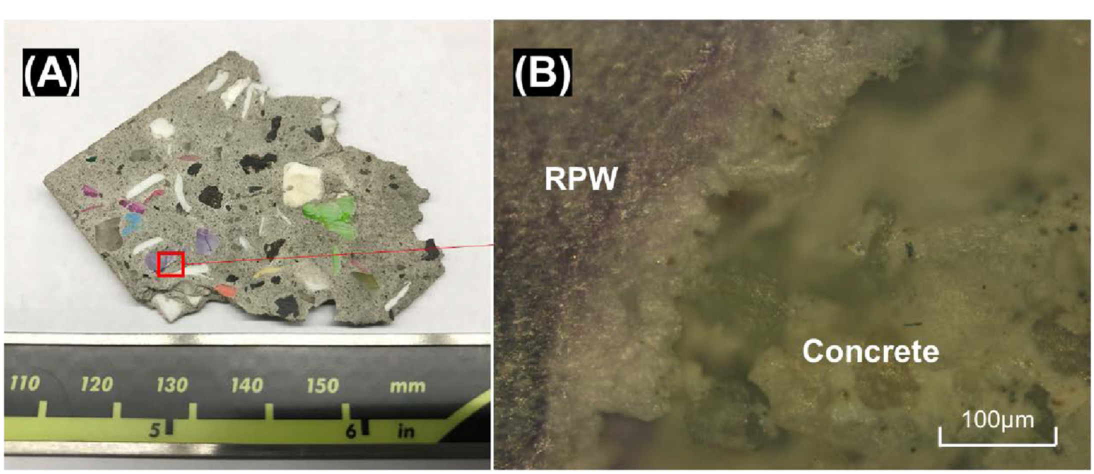


Fig. 9. Distribution of RPW in the top surface of water absorption sample: A) high-volume of RPW at the top surface of sample and B) an optical microscopic image showing voids between RPW and concrete.

and RPW in footpath concrete mix without reducing the strength properties of the concrete below the strength requirements set by road authorities and increasing the ductility of the final product utilizing the energy damping characteristics of the plastic aggregates.

4.4. Water absorption test

The water absorption of RCG and RPW was negligible. As a result, the total demand of water absorption in concrete was reduced in the presence of RCG [36]. According to Fig. 8, samples with 10% RCG and 10% RPW possess higher water absorption rates and sorption coefficients compared with the control samples. The moisture uptakes after 24 h was 33 and 40 g/cm^2 for the control and 10% RCG and 10% RPW samples respectively. While the sorption coefficients was estimated at 1.39 and 0.79 g/(cm$^2 \cdot \sqrt{}$min) for the control and waste-added samples, respectively. These data indicated that the field trial samples have a greater sorptivity than the control samples without RCG and RPW. Since the sorptivity has been widely deemed as an effective indicator for the durability of concrete [37,38], such results imply that the field trial samples with 10% RCG and 10% RPW may have a weaker durability performance compared with the control concrete sample with no addition of RCG and RPW.

In addition, it is worth noting that the water absorption results of the field trial contradicted with the previous results obtained from the laboratory test. The previous data [22] showed that the addition of RCG and RPW decreased the water absorption rates of samples, whereas the field trial results showed the incorporation of RCG and RPW increased the sample water absorption rate. This discrepancy can be attributed to the concentration of RPW around the top layers of samples and the low compaction of the field trial samples. Due to the water repellency of RPW, there would be a larger number of pores and voids formed around the RPW flakes within the samples. The concentration of RPW flakes in a certain area can further increase the porosity of the area, thereby resulted in a higher water absorption rate. This result was consistent with the finding of our previous laboratory study that the water absorption increased as the content of RPW increased [22]. Therefore, the water absorption of concrete samples was influenced by the distribution of pores and voids disrupted by the RPW flakes. Moreover, since the samples prepared in laboratory were made through sufficient vibration while the field trial samples were not subjected to any vibration therefore the two series of samples have different compaction degrees, which impacted the pores and voids development around RPW flakes. Loose samples would possess more pores and voids between RPW flakes and concrete.

According to the optical micrograph of the thin section of the water absorption sample shown in Fig. 9(b) the presence of voids between RPW and concrete on the surface is clearly visible. The presence of voids can increase the contact surface areas, resulting in higher water absorption rates.

5. Conclusions

A sustainable concrete footpath was constructed at Geddes Crescent Park in Hoppers Crossing, Victoria utilizing a design mix of 10% RPW and 10% RCG in a M40 concrete. Based on the results of this study, the M40 concrete incorporating 10% RPW and 10% RCG mixture met the local council standard for concrete footpaths in the state of Victoria.

A suite of laboratory tests comprising Unconfined Compressive Strength test, Indirect Tensile test and water absorption test along with non-destructive evaluation of field compressive strength of the footpath material using Schmidt hammer test was presented in this study.

UCS values of the tested footpath material after 28 days curing was 40.6 MPa and satisfied the UCS requirement of 20 MPa for the concrete to be used in footpaths in Victoria. In direct tensile stress of the tested footpath material after 28 days curing was 4.55 MPa and the value was above the recommended IDT stress value of 2.8 MPa. More than 95% of the tested spots along the footpath sections tested by Schmidt hammer showed compressive values higher than 25 MPa. Samples of the design mix showed a higher water absorption rates when compared with the control concrete sample. Finally, the results of this study showed that 10% RPW and 10% RCG of the concrete design mix has the potential to be incorporated in concrete footpaths as a sustainable material and this will lead to a significant reduction of the amount of plastic and glass wastes ended up in landfills.

Declaration of competing interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

CRediT authorship contribution statement

Yat Choy Wong: Writing - review & editing. **Sahan Perera:** Investigation, Writing - review & editing. **Zipeng Zhang:** Investigation, Writing - review & editing. **Arul Arulrajah:** Writing - review & editing. **Alireza Mohammadinia:** Writing - review & editing.

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